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Numbat nirvana: the conservation ecology of the endangered numbat *Myrmecobius fasciatus* (Marsupialia: Myrmecobiidae) reintroduced to Scotia and Yookamurra Sanctuaries, Australia

Matt W. Hayward[12*], Aline Si Lin Poh [13], Jennifer Cathcart[1], Chris Churcher[4], Jos Bentley[1], Kerryn Herman[1], Leah Kemp[1], Noel Riessen[1], Phil Scully[1], Cheong Hoong Diong[3], Sarah Legge[1], Andrew Carter[1], Heloise Gibb[4], J. Anthony Friend[5]

[1] Australian Wildlife Conservancy, Perth, Western Australia

[2] School of Environment, Natural Resources & Geography; and School of Biological Sciences, Bangor University, Deiniol Road, Bangor, LL572UW U.K. and Centre for African Conservation Ecology, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa

[3] National Institute of Education, Nanyang Technological University, Singapore

[4] La Trobe University, Melbourne, Victoria, 3086, Australia

[5] Department of Parks and Wildlife, Albany, Western Australia

[*] To whom correspondence should be addressed. m.hayward@bangor.ac.uk

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Dedication: We dedicate this paper to Jennifer Cathcart, whose passion for numbats drove much of this work and whose dedication to animal welfare improved practices at AWC.

Running header: *Numbat conservation ecology*

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Abstract

Despite a vigorous reintroduction program between 1985 and 2010, numbat populations in Western Australia are either static or declining. This study aimed to document the population ecology of numbats at two sites that are going against this trend: Scotia Sanctuary in far western New South Wales and Yookamurra Sanctuary in the riverland of South Australia. Scotia (64,659 ha) and Yookamurra (5,026 ha) are conservation reserves owned and managed by the Australian Wildlife Conservancy and where numbats were reintroduced in 1999 and 1993 respectively. Both sites have large conservation fence protected introduced species-free areas where there are no cats *Felis catus* or red foxes *Vulpes vulpes*. Numbats were sourced from both wild and captive populations. From small founder populations, the Scotia numbats are now estimated to number 169 (113–225) and 44 at Yookamurra. Radio collared individuals at Scotia were active between 13 and 31ºC. Females had home ranges of 28.3 ± 6.8 ha and males 96.6 ± 18.2 ha, which leads to an estimated sustainable population or carrying capacity of 413–502 at Scotia. Captive bred animals from Perth Zoo had a high mortality rate upon reintroduction at Scotia due to raptor predation and starvation. The habitat preferences for mallee with a shrub understory appear to be driven by termite availability, and other reintroduced ecosystem engineers appear to have been facilitators by creating new refuge burrows for numbats. This study shows that numbats can be successfully reintroduced into areas of their former range if protected from introduced predators, and illustrates the difficulties in monitoring such cryptic species.

Introduction

The numbat *Myrmecobius fasciatus* is a medium-sized (300–715g) marsupial (Friend 1990) that is unique among marsupials in being diurnal and exclusively termitivorous (Calaby 1960; Cooper 2011). The numbat has suffered a massive reduction in population size and geographical distribution in the last two centuries (Friend 1990; Peacock 2006). From an original distribution that spanned semi-arid and arid Australia from western New South Wales, through South Australia to the southern border of the Northern Territory and the southern half of Western Australia, its range became restricted to only two sites (Dryandra and Perup) in south-western Western Australia by the mid-1980s (Fig. 1; Friend and Thomas 1994, 2003).

The decline in numbat populations continues and the number of populations is estimated to have decreased by more than 20% in the past five years (2008–2013), with the global population estimated at less than 1000 individuals in the wild and several reintroduction attempts now considered as failures such that the numbat is currently listed as endangered on the IUCN Red List (Friend and Burbidge 2008a). It is also listed as presumed extinct in New South Wales and South Australia. Causes of this dramatic reduction were originally considered to be predation by the introduction of the predatory red fox *Vulpes vulpes* and habitat loss and degradation, ironically fox control may have resulted in mesopredator release and cats have now become a major predator (Friend and Burbidge 2008a, 2008b; Friend *et al.* 2013).

Between 1985 and 2010, numbats were reintroduced at nine sites in the south-west of Western Australia: Boyagin (1985), Karroun Hill (1986), Tutanning (1990), Batalling (1992), Karakamia (1994), Dragon Rocks (1995), Dale (1996), Stirling Range (1998) and Cocanarup (2006). In 2005, a trial translocation was carried out to Roxby Downs in South Australia. At

Boyagin, Tutanning, Batalling and Dragon Rocks, the reintroductions were successful and populations persist today. Failures at the other sites were caused by a range of factors. At Karroun Hill, heavy predation by feral cats was the most likely cause and at the Karakamia fenced sanctuary, the enclosed area was too small to support a viable population. At Dale in the northern jarrah forest, most animals dispersed too far from the release site to form a breeding population. At Stirling Range, fox control was difficult to maintain in wet seasons and at Cocanarup the activities of a wide range of predators, including birds of prey, foxes, cats, chuditch, monitors and pythons combined to critically limit population growth (Friend and Thomas 2003; Friend *et al.* 2013). The trial at Roxby Downs produced some promising results, but only five animals were released and three, including both females, were taken by raptors within eight months (Bester and Rusten 2009).

Due to the magnitude of the species' range reduction and dramatic decline in the number of individuals in the wild to a few remaining sites, programs of reintroduction and establishment of additional numbat populations are still considered essential for the conservation of the species despite the setbacks described above (Friend and Burbidge 2008a). At present, the vast majority of published information on numbat ecology comes from studies conducted in the south-west of Western Australia (Calaby 1960; Christensen *et al.* 1984; Friend 1990; Cooper and Withers 2004, 2005), with individual studies conducted in New South Wales (Vieira *et al.* 2007) and South Australia (Bester and Rusten 2009). Ecological studies conducted on numbat populations located in Western Australia may not be directly applicable to the same species in New South Wales and South Australia due to differences in climate, primary productivity, habitat types, termite species diversity and abundance and also the impact of human activities on the landscape. To ensure future reintroduction success of this species back into these environments, it is critical to bridge the

gap in the available information on numbat populations found in the arid and semi-arid environments located in New South Wales and South Australia.

Here, we aimed to document the reintroduction history of the numbat populations at Scotia and Yookamurra sanctuaries, which both lie within the numbats' former range but outside the species 'stronghold' of Western Australia. This included estimates of population size and dynamics, survivorship and habitat use, while highlighting the difficulties in monitoring small, cryptic species. We further aimed to estimate the carrying capacity of our sites using home range size as home ranges do not overlap within sex and sexes are at parity (Friend 2008; Friend *et al.* 2013), and home range size tends to be related to resource availability (Nilsen and Linnell 2006; Hayward *et al.* 2009). Although numbats have been the focus of conservation efforts for over 30 years, these two sanctuaries are the only sites at which this species has been established outside Western Australia, despite the species' historically broad distribution. We discuss potential factors causing this apparent apathy by some conservation agencies to remedy this deficiency by reintroducing numbats beyond Western Australia and what the success of these reintroductions illustrate about the decline of critical weight range mammals in Australia. In light of the regular calls for reviews of reintroduction/restoration programmes (Breitenmoser *et al.* 2001; Macdonald 2009; Wortley *et al.* 2013), this review is timely and important.

Study sites

The study was conducted at Scotia and Yookamurra sanctuaries. These two wildlife sanctuaries are privately-owned and managed by the Australian Wildlife Conservancy (a not-for-profit conservation organization; AWC). Scotia is a 64,659 ha protected area located in far western New South Wales (Fig. 1.). Within the sanctuary, two conservation fences, each protecting ~4,000 ha areas named Stage 1 and Stage 2, have been built and all non-native

mammals, such as foxes, cats *Felis catus*, goats *Capra hircus* and European rabbits *Oryctolagus cuniculus,* have been removed (AWC 2011). As part of the Scotia Endangered Species Recovery Project, burrowing bettongs (*Bettongia lesueur*), brush-tailed bettongs (*B. penicillata*), greater bilbies (*Macrotis lagotis*), bridled nailtail wallabies (*Onychogalea fraenata*), greater stick-nest rats (*Leporillus conditor*) and numbats (*Myrmecobius fasciatus)* have been reintroduced (AWC 2011).

There are four main vegetation communities at Scotia that occupy 95% of the area: *Casuarina pauper* woodland, mallee *Eucalyptus* spp. with a shrub understorey, mallee with a spinifex *Triodia scariosa* understorey, and mixed shrubland (Westbrooke *et al.* 1998; AWC 2005; Westbrooke 2012). Scotia Sanctuary occurs on the boundary of Australia's arid and semi-arid climatic zones, with an average rainfall of 250 mm. The region experiences hot summers (December to March) with mean daily maximum temperatures over 30°C and cool winters with mean daily temperatures below 17°C. The annual temperature extremes range from -6°C to 47°C.

Yookamurra is a 5026 ha sanctuary located in the Murraylands of South Australia (Fig. 1). Yookamurra has 1092 ha confined within a conservation fence similar to Scotia's and similar species were reintroduced following the eradication of foxes, cats, goats and rabbits. This area is vegetated by mallee with a shrub understorey growing on shallow soils over a thick layer of calcrete. Yookamurra receives 270 mm of rain annually. Southern Australia was gripped by drought for almost a decade until Spring 2010 when La Niña conditions returned and the region received up to twice the annual average rainfall.

Earth Sanctuaries Ltd (De Alessi 2003) and the Western Australian Department of Conservation and Land Management (now Parks and Wildlife) released 15 numbats from Dryandra at Yookamurra in 1993. Five males and a female without dependent young were transferred from the wild population at Dryandra by air and road to Yookamurra on 9th

November 1993, followed on 7th December by nine females whose young had been weaned. By 1996, numbats were sighted frequently in all vegetation types within the sanctuary. No subsequent additions of numbats have occurred at Yookamurra, although eight individuals were moved from there to the Stirling Range National Park in Western Australia on 8th December 1999.

In November 1999, 19 numbats were captured at Yookamurra, transported by road to Scotia and released into previously selected hollow logs in mallee/shrub habitat. These were supplemented in November 2000 with an additional 24 individuals from Yookamurra. No additional animal movements into Scotia occurred until the population was supplemented in 2011 by 13 and in 2012 by a further 17 captive-bred numbats from Perth Zoo. We document the survivorship and spatial ecology of those individuals below.

Methods

Population monitoring

Numbats were monitored using three distinct methods. Firstly, an index of tracks (Allen *et al.* 1996) has been used to monitor them at Scotia since 2002 by 'dusting' a series of dirt tracks for several kilometres in the early morning and then counting the number of tracks visible that afternoon. The soil at Scotia dries to form a very fine dust that is most amenable to tracking. This was repeated over four days and we present this index as a 'track index'. We acknowledge the deficiencies of this method in that it ignores detectability (Hayward and Marlow 2014; Hayward *et al.* 2015), but present these data to provide a long-term perspective. The track index determined for autumn is most indicative of population size during the preceding summer, although we present data for all surveys conducted. The track index method was not conducted at Yookamurra due to the unsuitable substrate. Secondly, we employed the standard monitoring method for number of numbat observations per 100 km

of driven transect during their peak activity periods ('observation index'; 7–10 am and 5–9 pm based on temperature) in summer (December) at Scotia and Yookamurra (Friend 1994; Friend and Thomas 2003). Finally, we estimated the population at both sites using sightings along strip transects derived from driven transects during their peak activity periods ('estimates') because we were unable to meet the assumptions of Distance Sampling (Buckland *et al.* 2001). Seventy-seven (77) transects (120–500 m long) were situated on tracks throughout Stage 1 at Scotia (1 km long in 2014) and 7 at Yookamurra, reflecting the density of vehicle tracks through both sites. Numbats were only recorded when on a transect. Perpendicular distances were measured using a range finder to determine the strip width. The length of transects along fence lines was halved to account for numbats only occurring on one side (Buckland *et al.* 2001).

Observation surveys were conducted from November through to early February in 2010, but ended in December thereafter as this was the period of peak population size when numbat young disperse (Friend 2008). These methods were not conducted concurrently but the latter methods were included in the monitoring program when we recognised the limitations of the earlier methods.

Observation and capture methods

For observations and captures, teams of three or four individuals drove at approximately 15 km hr^{-1}. Once a numbat was sighted, the location was recorded (observation index or estimates) or, if animals were to be captured for radio collar fitting, we stopped the vehicle and captured the animal by chasing it into a retreat site, then covering the exits with fishing netting and coaxing the animal to flee into the nets by blowing air through 10 mm diameter plastic tubing or by digging it out. The numbat was then placed into a cotton bag to reduce stress and either processed in the field or taken back to the laboratory for a

200 short examination when measurements and genetic ear tissue samples were taken and for the
201 radio collar to be attached. We compared the body mass of Scotia numbats with published
202 data on Dryandra males (Friend 2008) to assess the relative condition.
203
204 *Radio telemetry, home range, carrying capacity and survivorship estimation*
205 At Scotia, seven males from Stage 1 were fitted with Sirtrack® VHF radio collars (12
206 g) and reintroduced to Stage 2 in 2009. An additional six females were fitted with radio
207 collars in Stage 1 in 2010/2011. Radio collars were less than 5% of the adult body mass and
208 so were assumed not to disturb their natural behaviour (Cochran 1969). After fitting radio
209 collars, the animals were returned to the location they were captured and followed visually to
210 ensure there were no adverse reaction to their collars. Subsequently, radio collared numbats
211 were recaptured once every three to six weeks to ensure that the radio collar was
212 satisfactorily fitted for growing animals. Radio collars were replaced once every three months
213 prior to battery failure.
214 Initially, radio collared numbats were located hourly during daylight, however this
215 was reduced to once a day after a month. These locations occurred during periods of peak
216 activity between 7 am and 12 pm or between 2 pm and 7 pm in summer and between 10 am
217 and 5 pm in autumn (Christensen *et al.* 1984; Friend 1986). Numbats were located once a day
218 to avoid the underestimation of home ranges caused by autocorrelation of fixes. We used
219 triangulation to determine the location of each numbat, whereby a minimum of three compass
220 bearings were obtained towards the strongest telemetry signal within 10 minutes to minimize
221 any location error due to movement. Point locations from ground telemetry were estimated
222 within a 95% error ellipse using the program Locate III (Nams 2006). We calculated mean
223 ground telemetry error as 57 m, based on 10 locations on daytime retreats following Hayward

et al. (2004). Where possible, locations determined by sighting of the numbat were used in the analysis.

Previous studies on the home range of numbats have used as few as 10 locations and up to 37 locations to estimate home range (Christensen *et al.* 1984; Bester and Rusten 2009). It is well documented that the number of locations affects the size of the home range estimated (White and Garrot 1990; Seaman and Powell 1996; Seaman *et al.* 1999). Incremental area analysis was undertaken to determine the number of locations required to accurately estimate within 90% of the total estimated home range of the numbats (Kenward and Hodder 1992; Hayward *et al.* 2004). Utilisation curves were used to determine the core home range (Kenward and Hodder 1992), which we defined as the point where the mean home range size deviates from a linear trend, accounting for standard error.

Home range size was considered to be the area within which an individual occurs 95% of the time. For each numbat, home-range size was estimated using 95% MCP, kernel and harmonic mean methods. The software Ranges7 Lite (South *et al.* 2008) was used to estimate the home range for each method. Overall home range was calculated using all telemetry fixes obtained in summer and autumn. For seasonal analysis, summer was designated as December–February and autumn as March–May.

The core home range of the numbat was defined as the core area within which an individual was found to occur 50% of the time. To estimate the percentage of telemetry fixes needed to estimate the core home range, a utilization plot was created using the kernel estimator (Hayward *et al.* 2004).

We estimated carrying capacity (K) using the equation:

$$K = \frac{2A}{H}$$

where A = area of numbat range and H = mean area of female kernel home range estimate. This value is multiplied by 2 to account for males given the 1:1 sex ratio and because adult

numbats are solitary and territorial, with females occupying exclusive home ranges that overlap with those of males (Friend and Burbidge 2008b). This method accounts for habitat availability at a site through the variation in home range size associated with habitat.

We estimated survivorship of radio collared individuals using the known fates model in Program MARK with model selection to test the effect of the release method and heterogeneity using Akaike's Information Criteria and Akaike's weights (w) to represent the support for the model (White and Burnham 1999). Estimated known fate survival is presented along with 95 percentile confidence intervals.

Activity patterns at den

Reconyx Hyperfire cameras were placed near the entrance of two overnight dens of two of the radio collared female numbats for 21 days and 6 days respectively in summer 2011. These recorded the activity around the den, the time of day and the ambient temperature when each photograph was taken. We define dens as overnight resting sites for numbats, and retreat sites as dens plus bolt holes used for predator refuge during the day.

Habitat preference

Habitat preference was determined using Jacobs index (Jacobs 1974), which is a derivation of Ivlev's electivity index (Ivlev 1961) that is independent of the relative abundance of the habitat type (Krebs 1978). The value of *D* is calculated as

$$D = \frac{r - p}{r + p - 2rp}$$

where *p* is the proportion of a habitat type in a numbats' home range and *r* is the proportion of locational fixes occurring within that habitat type. Jacobs index values range from +1 (maximum preference) to – 1 (maximum avoidance) with values near zero indicating use of a habitat type in proportion to that habitat's availability within the home range (Krebs 1978).

To determine the proportion of habitat types present within each home range, the shape file created for the 100% MCP home ranges using the software Ranges7 Lite (South *et al.* 2008) was overlaid onto a vegetation map of Scotia using the QGIS software (QGIS 2011). This allowed for the area of each habitat type to be determined.

We measured foraging effort within each habitat of each male numbats' home range using four randomly selected locations and recording numbat diggings along 100 m band transects of 4 m in width (total of 16 sites per numbat). To avoid overlap, transects were established (where possible) in a north, south, east and west direction within each habitat. Numbat diggings are relatively easy to distinguish from diggings of other species present in the study area (Triggs 1996; Moseby *et al.* lcu) and are usually small, ranging from 40–70 mm in length and up to 20 mm deep.

Termite abundance at Scotia was assessed using two methods. Within each habitat type in Stage 1, ten random survey sites were selected and termite abundance was assessed following the method described by Friend (2004). At each survey point, two 10 m lines intersecting at right angles at the 5 m mark were measured. Leaf litter on the surface was scraped away to expose the soil surface. A spade was used to dig furrows 40 mm deep along the lines. The number of exposed active termite galleries at each site was counted. The survey was carried out in summer and autumn and the seasonal data were pooled according to habitat type. The second method was carried out in Stage 2 where ten random locations were selected from each of the four habitats and ten toilet rolls were buried to 1 cm below the soil surface at each site. Leaf litter was removed for toilet roll burial and then replaced. Toilet roll baits are a standard sampling method for termites, but may not sample the entire species assemblage (Dawes-Gromadzki 2003). Toilet rolls were buried in two rows of five, each roll spaced five m apart and were left buried for three months. After this time, they were dug up, and the percentage of toilet rolls consumed by termites was estimated. Termites encountered

299 during the retrieval of the toilet rolls were collected and stored in ethanol. Special care was
300 taken to ensure termite soldiers were collected, as most identification keys are based on this
301 caste. All termites collected from the toilet roll transects were identified to genus level using
302 a dichotomous key (Watson 1988). Toilet-paper rolls have been widely used in studies of the
303 distributions and activity of wood-feeding termites in North America, Australia and Africa
304 (La Fage *et al.* 1973; Abensperg-Traun 1993; Dangerfield and Schuurman 2000). While the
305 toilet roll method does not collect all species, it provides relative abundance/occurrence for
306 species attracted to that bait type. A previous study in northern Australia showed that buried
307 toilet rolls are more effective than baits left on the surface and more attractive than wood
308 baits in the long term (Dawes-Gromadzki 2003).
309 We determined the abundance of potential retreat sites (dens and bolt holes such as
310 hollow logs or bilby/boodie burrows) within each of the four major habitats in Stage 2 by
311 selecting ten randomly distributed sites within each habitat. Retreat sites were surveyed along
312 100 m band transects of 10 m width at each site (total of 40 sites). The type and abundance of
313 all potential retreat sites on the transect were recorded. Potential retreat site types included
314 any hollow, log or burrow that had an entrance diameter between 70 and 130 mm based upon
315 previous reports of preferred numbat retreats (Christensen *et al.* 1984).
316
317 *Data analysis*
318 Two sample t-tests were used to determine whether there was a significant difference
319 in seasonal home ranges or exposed active termite galleries between each habitat site. To
320 determine whether a habitat was preferred or avoided, one-sample t-tests were carried out to
321 determine whether the mean value of the Jacobs index was significantly different from zero
322 (Palomares *et al.* 2001). Habitat units that showed no variation in Jacobs index (i.e., those
323 always – 1) were not tested with t-tests but were considered as being significantly avoided.

The statistical software Minitab 16 (2010) was used to carry out the analysis. Means are presented ± 1 S.E.

Results

Population monitoring

Scotia's numbat track index was relatively constant when compared at the same season between 2003 and 2007, whereupon it declined to around one track per km during 2008 to 2010 before increasing in 2011 and 2012, and then declining in 2013 to 2010 levels (i.e. to pre-La Niña levels; Fig. 2). There was no relationship between the number of tracks recorded and the temperature during the survey ($r^2 = 0.075$, n = 7, $p > 0.10$). A mean of 787 ± 73 km of observation transects were driven each year at Scotia. The observation index did not reflect the track index in this radical increase in 2011, but rather suggested the increase had occurred by 2010 before declining in 2012 (Fig. 3). The numbat population at Scotia was founded with 43 individuals (from Yookamurra) in 1999–2000 and early reports suggested the population was fairly constant at this level, while population estimates since 2010 have ranged from 50 and 202 (most recently for both stages is 169, December 2014; Fig 4).

A mean of 715 ± 199 km of observation transects were driven at Yookamurra and the observation index suggested the population has increased since 2011 (Fig. 3). Strip transect population estimates are of 44 individuals occurring at Yookamurra in 2014 (Fig. 4).

Morphology

Female numbats (and their young) captured for radio tracking weighed a mean of 360 ± 35 g (range: 262–485 g; Fig. 5). When recaptured four months later, they had increased in body mass (409 ± 30 g) by 20 ± 6%. All females, except one, had young attached upon first capture (2.3 ± 0.6 young/female) and all female weights include young. The female numbats

monitored repeatedly in Stage 1 exhibited the typical variation in adult body mass associated with growing pouch young, deposition in a den/nest and then lactation (Fig. 6).

Male numbats translocated from Stage 1 to Stage 2 at Scotia weighed 402 ± 32 g upon release (range: 260–600 g) and 462 ± 38 upon recapture two months later in Stage 2 (Fig. 5). Females captured in Stage 1 weighed 356 ± 33 g and when recaptured in Stage 1 weighed 405 ± 13 g and 300 ± 25 g in Stage 2 (Fig. 5). The body masses of Scotia numbats overlap the range found at Dryandra (305-647 g for females and 405-752 g for males; from Friend 2008).

Activity patterns

Mean den exit time of two radio collared animals was 0942 h (range: 0844–1040 h) and mean temperature of the environment at that time was 17 ± 1° C (range: 13–22°C). Mean den entry time was 1732 h (range: 1652–1752 h) and mean temperature at that time was 25 ± 1° C (range: 22–31° C). Mean length of time numbats stayed in the overnight refuge was 16 hours (range: 15–18 hrs). Numbats were inactive at night and did not return to the overnight refuge during the day.

Home ranges

In total, 340 locations were recorded for the five radio collared female numbats and 213 for the six males. The mean number of summer locations was 40 ± 2 locations per female numbat and 35 ± 1 locations in autumn. The mean number of locations for males was 36 ± 1 and these were restricted to summer. Incremental area analysis revealed 45 radiolocations were required to estimate to within 90% of the overall home range area, so the male ranges should be considered as summer ranges only. Utilization plots using mean home ranges of

numbats determined by the kernel estimator showed that core home range occurred at 50% of fixes for females and 60% of fixes for males.

The mean (± SE) kernel home range size of female numbats was 28.3 ± 6.8 ha, while the mean core range size was 10.9 ± 2.4 ha. The mean (± SE) kernel summer range size of male numbats was 96.6 ± 18.2 ha, while their mean core summer range size was 30.6 ± 6.0 ha. The summer kernel home range size of females was 36.5 ± 11.9 ha, while for autumn that declined to 12.7 ± 2.6 ha. There was no significant difference in seasonal home range size for female numbats ($t_4 = 1.96$, $p = 0.122$).

Carrying capacity

The area available to numbats within Stage 1 of Scotia is approximately 3700 ha (the remaining 300 ha consist of separate captive breeding areas). Given a home range size for female numbats of between 28.3 and 38.9 ha and for males between 51.1 ha and 96.6 ha, we estimate Scotia's Stage 1 has the potential to support between 95–131 females and 38–72 males, and the 4000 ha in Stage 2 between 103 and 141 females and 41 to 78 males. This yields a total population of between 413 to 502 numbats, which is 2.2 to 3.7 times greater than the current population estimates (Fig. 4).

Survivorship and mortalities

Six of the seven radio collared female numbats in Stage 1 survived the six month study period. One individual died during recapture (Fig. 7).

Of the six radio collared male numbats translocated to Stage 2, one died after four weeks while the remainder survived the three month study period. The cause of death could not be determined for this individual. There was insufficient data to derive known fate survival estimates for this group of animals.

The captive-bred numbats sourced from Perth Zoo had a high mortality rate with 80% of animals either dying or their collars failed. The known fates survivorship of these animals was 0.13 ± 0.02 for the 27 week duration of the telemetry study. Raptor predation (primarily brown goshawk *Accipter fasciatus* as many carcasses were found either within or below nests) was attributed as the main cause of death for the 2011 captive-bred animals, while starvation was the main cause of death for the 2012 animals, when drought conditions returned (Fig. 7). The differences between mortality causes for the wild monitored and the two Perth Zoo releases were significant (χ^2 = 18.87. d.f. = 6, p = 0.004).

Habitat preferences

There was strong similarity in habitat preferences for male and female numbats at Scotia, with mallee with a shrub understorey being most preferred (Fig. 8). Female numbats significantly avoided mallee with a spinifex understorey (t_5 = 2.97, p = 0.041), but used the remaining habitats in accordance with their availability (Fig. 8). Male numbats avoided the shrub habitat (t_3 = -3.496, p = 0.040), but used the remaining habitats in accordance with their availability (Fig. 8).

There was no significant difference in termite abundance between the habitat types in Stage 1 using the standard method of assessing termite availability for numbats (H_3 = 4.24, p = 0.237). The highest mean number of active termite galleries per 20 m transect length was in the *Casuarina pauper* woodland with 3 ± 1 galleries, followed by mallee habitats and the mixed shrubland (Fig. 9). There was a significant difference in termite activity as measured by toilet roll consumption by termites across the four habitats in Stage 2 (χ^2 = 13.51, df = 3, p = 0.004). A significantly greater percentage of toilet rolls was consumed in the mallee spinifex habitat, than the shrub habitat ($U_{(19)}$ = 12.50, p = 0.005) and *Casuarina* habitat ($U_{(19)}$ = 7, p = 0.001). Termite activity did not differ between the mallee shrub habitat and the

mallee spinifex habitat ($U_{(19)} = 30.50$, $p = 0.140$), shrub habitat ($U_{(19)} = 25.50$, $p = 0.064$) or the *Casuarina* habitat ($U_{(19)} = 30.00$, $p = 0.131$). Nor did termite activity differ between the shrub and *Casuarina* habitats ($U_{(19)} = 46.50$, $p = 0.791$). Termite abundance was dominated by the genus *Heterotermes*, which were the most abundant in all habitats (Table 1). We also found species of *Amitermes* in very low abundances in all habitats and *Nasutitermes* in the mallee shrub and shrub habitats.

The relative abundance of male numbat diggings at Scotia was significantly different between the four habitats in Stage 2 ($\chi_{(3)}^2 = 24.31$, $p < 0.001$) with significantly more diggings found in the mallee shrub habitat than in the shrub habitat ($U_{(47)} = 104.50$, $p < 0.001$), mallee spinifex habitat ($U_{(47)} = 59.00$, $p < 0.001$) or *Casuarina* habitat ($U_{(47)} = 178.50$, $p = 0.023$). There was no significant difference between the abundance of diggings in the *Casuarina* habitat and the mallee spinifex habitat ($U_{(47)} = 268.50$, $p = 0.680$). There was also no significant difference between the numbat diggings in the shrub habitat, *Casuarina* habitat ($U_{(47)} = 224.00$, $p = 0.179$) and mallee spinifex habitat ($U_{(47)} = 196.50$, $p = 0.055$).

There was no significant difference in the number of retreat sites across the four habitats ($F_{(3,39)} = 309.90$, $p = 0.127$) with animal burrows as common as the more traditionally important hollow logs. The abundance of log hollows differed between the four habitats however ($\chi_3^2 = 8.707$, $p = 0.033$), with significantly more hollows found in the mallee spinifex habitat than the shrub habitat ($U_{(19)} = 22.50$, $p < 0.05$) possibly reflecting fire history, but no differences between any other habitat types ($p > 0.05$ in all cases).

Discussion

Numbats have increased at Scotia and Yookamurra following release. Populations have persisted for one and two decades respectively, highlighting that this is a readily conservable species provided the agents of its decline—introduced foxes and cats—are

448 removed. Intensive and long-term fox control at Dryandra has not been enough for long-term
449 population recovery (Friend *et al.* 2013) suggesting that much lower numbers or the complete
450 eradication of foxes and cats is required, unless the newly developed Eradicat control
451 (Hetherington *et al.* 2007) or apex predator reintroduction (Ritchie *et al.* 2012) are successful.
452 If we cannot control mesopredator release of cats, then we will require the creation of
453 offshore island populations via marooning (Dickman 1992; Burbidge *et al.* 1997; Short 2009)
454 or mainland island populations via conservation fences (Dickman 2011; de Tores and Marlow
455 2012; Hayward *et al.* 2013). While fencing may be considered an acknowledgement that our
456 existing conservation practices have failed (Hayward and Kerley 2009), recent research has
457 recommended fencing for large, charismatic and highly mobile species (Packer *et al.* 2013)
458 and the aversion to such intensive conservation management practices by politicians and
459 practitioners alike should end before it is too late for so many species. Creating introduced
460 species-free areas is expensive, disheartening for people intent on 'hands off' approaches to
461 conservation and will require political will, but it seems the surest strategy to ensure
462 conservation success in the face of limited conservation funds. However, in reality there are
463 few if any successful 'hands off' conservation methods.
464 Scotia's numbat population responded rapidly to the *La Niña* rains, however the latest
465 population estimate for Scotia Stage 1 (86) is still well below our predicted carrying capacity
466 of 138 to 203. This may be due to methodological problems of carrying capacity estimation
467 or changes in resource availability since the end of the drought. Numbats at Dryandra are
468 less likely to exhibit such rapid population increases following periods of resource abundance
469 due to the dampening effect of introduced predators there and/or the likely difference in
470 resource levels. However we are unable to rule out methodological differences as the cause
471 of this difference.

Numbats are an immensely difficult species to monitor. They are trap shy, so mark-recapture methods do not work. They occur at low densities, so camera trapping and photo mark-recapture does not work. They are rarely spotted, so Distance Sampling requires thousands of kilometres of driven transect and substantial time investment to obtain sufficient observations; even so, some key assumptions of distance sampling may not hold in track-based surveys in dense vegetation, such as the mallee scrub on Scotia and Yookamurra. Yet, our results illustrate that the indices used to monitor numbats do not necessarily correspond to the population estimates (Fig. 2-4). The fundamental reason for this is that inter-annual climate variation particularly is likely to alter the detection probability of all methods of assessment used and so detectability should be accounted for in monitoring methods. Distance Sampling does this and therefore theoretically provides the most robust population monitoring tool (Buckland *et al.* 2001). Nonetheless, we were unable to satisfy all assumptions of Distance Sampling as tracks used for transects were established in a rough grid prior to our monitoring beginning and have not been placed randomly. Longer-term intensive monitoring will be required to determine the most effective and cost efficient monitoring method for numbats at our sites using all three methods.

Numbats have been studied extensively in Dryandra (Western Australia), however little work has been published from elsewhere in their range. There is no reason to believe numbats at Dryandra behave ecologically as all numbats once did and the variation between the Dryandra results and ours highlights the critical importance of replicated research on the autecological variability of threatened species. At Scotia and Arid Recovery in South Australian where numbats have also been reintroduced, numbats increase their home range size in summer (48.5 ha cf 20.5 ha in autumn; Bester and Rusten 2009). This may be due to increased water requirements in these more arid sites at this time of year or the earlier onset of reduced male activity over the cooler months there.

497 The selection for mallee with shrub understorey habitat and avoidance of mallee with
498 spinifex understorey detected at Scotia is most likely linked to termite accessibility (rather
499 than abundance). The mallee with shrub understorey habitat had a greater abundance of
500 numbat diggings, suggesting increased foraging effort. Avoidance of the mallee with spinifex
501 understorey habitat is supported by other work at Scotia that found a preference for habitats
502 with fewer spinifex hummocks and less bare soil (Vieira *et al.* 2007). It is less clear whether
503 *Casuarina* provided many resources despite numbats being regularly detected there, as we
504 found little evidence of foraging activity.
505 Habitat preferences may be driven by a number of factors, including natural enemies
506 and resource availability. Although there were no exotic mammalian predators within the
507 fenced areas of Scotia, avian and reptilian predators still represent a significant risk to
508 numbats. For example, a high proportion of numbat mortality in reintroduction programs has
509 resulted from predation by raptors (our data; Friend and Thomas 2003; Bester and Rusten
510 2009). The *Casuarina* and mallee habitats probably provide more understorey and canopy
511 cover than the shrub habitat (Westbrooke *et al.* 1998), allowing for greater protection from
512 predators.
513 Resource availability is also likely to determine numbat habitat use, with food and
514 retreat sites likely to be particularly important. Our surveys of the activity of termites, the
515 key food source of numbats, suggested that termites were least abundant in the shrub and
516 *Casuarina* habitats, preferring the mallee. Termites feed on wood, leaves, bark and grass,
517 with some species feeding only on decaying wood (Hadlington 1996). As the ground in the
518 shrub habitat appeared to lack many of these components, and the primary plant species
519 there, *Dodonaea viscosa*, may even be termite-resistant (HDRA 2001 in Churcher 2010), it is
520 possible that there are few food resources available for termites in this habitat type through an
521 absence of dead wood or difficulty in traversing the hard soils. However, the *Casuarina*

habitat, which also supported low termite activity and little evidence of numbat foraging, was used frequently by numbats. This suggests that termite availability may not be the only determinant of numbat habitat use. It is also worth noting that, because we sampled termites using baits, we collected only the subset of termite species attracted to those baits, in particular *Heterotermes* sp. This could mean that many species consumed by numbats, which are generalist termitivores (Christensen *et al.* 1984), were missed in termite surveys employed as part of numbat research and there is clear variation between habitats on the optimal monitoring technique for termites (Davies *et al.* 2013). This could include species feeding inside logs.

The availability of most retreat sites was similar across habitats, although hollow retreats were more abundant in mallee spinifex than shrub habitat, with other habitats intermediate. Scotia and Yookamurra support a variety of critical weight range mammals, including ecosystem engineers, such as the bilby and the burrowing bettong. The presence of these species is likely to have led to greatly increased numbers of burrows. It seems likely that facilitation has occurred via more burrows being available for numbats than there would be in the absence of the reintroduced ecosystem engineers. If this is the case, retreat sites may not be limiting in the study area. This might explain the poor relationship between numbat site selection and retreat site availability. Given the higher insulation value of burrows compared to hollow logs (Cooper & Withers, 2005), we would predict that longer term telemetry would reveal numbats spending more time in burrows during temperature extremes (i.e. summer and winter) compared to more moderate periods. This also highlights the importance of reintroducing the entire suite of regionally extinct species to allow such unexpected (facilitation) interactions to occur.

Despite concerns that arid and semi-arid ecosystems have been damaged beyond repair for much of Australia's wildlife (Lunney 1994; Dickman *et al.* 2002), there is little

evidence of this for the resources necessary to sustain numbats (evidence presented here) or many other locally extinct native fauna (Hayward *et al.* 2010). It now seems likely that restoration of these regions requires protection from introduced predators and the reintroduction of native fauna, rather than simply the restoration of vegetation. The persistence of numbats at Scotia and Yookamurra highlights the value of conservation fences and intensive conservation action. Given the parlous state of numbats in Western Australia (Friend *et al.* 2013), it is now imperative that resources are directed toward effective conservation actions, such as fencing and reintroduction. This is legislated for in NSW as the numbat is listed as presumed extinct (NSW TSC Act 1995) and so there is no driver for the government conservation agency to reintroduce the species. Altering the legislation to provide a conservation focus on all extant species that once occurred there or to consider only regionally extinct species would provide a powerful stimulus for such action.

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763

764 **Table 1. Termite captures at Scotia using the toilet roll method.**

765

Method	Habitat	n	*Amitermes*	*Heterotermes*	*Nasutitermes*
Transect	Casuarina	2	0.0 ± 0.0	0.5 ± 0.5	0.0 ± 0.0
	Dodonaea	2	0.0 ± 0.0	0.5 ± 0.5	0.0 ± 0.0
	Mallee Shrub	3	0.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.3
	Triodia Mallee	1	1.0 ±	0.0 ±	0.0 ±
Toilet Roll	Casuarina	9	0.1 ± 0.1	1.2 ± 0.3	0.0 ± 0.0
	Dodonaea	8	0.3 ± 0.2	0.5 ± 0.4	0.1 ± 0.1
	Mallee Shrub	9	0.2 ± 0.1	1.1 ± 0.3	0.0 ± 0.0
	Triodia Mallee	10	0.1 ± 0.1	2.2 ± 0.5	0.0 ± 0.0

766

Figures

Figure captions

Fig. 1. Distribution map of the numbat including sites referred to in the text. Original extant sites are shown in blue, other reintroduction sites in green.

Fig. 2. Track index of numbats at Scotia (Stages 1 and 2) between spring 2003 and autumn 2013 based on the mean number of footprints detected per kilometre of dusted transect. Given the annual pattern of activity of numbats is driven by temperature, only index values from the same seasons are comparable and autumn is the most relevant season as young have grown and entered the population and it is before the period of inactivity over winter.

Fig. 3. Observation index of numbats at Scotia and Yookamurra based on the mean number of numbats observed daily per 100 km of driven transect. Only Stage 1 at Scotia was monitored in this fashion due to the low density of the newly established numbat population in Stage 2.

Fig. 4. Population estimates of numbats at Scotia and Yookamurra based on strip transects since 2010.

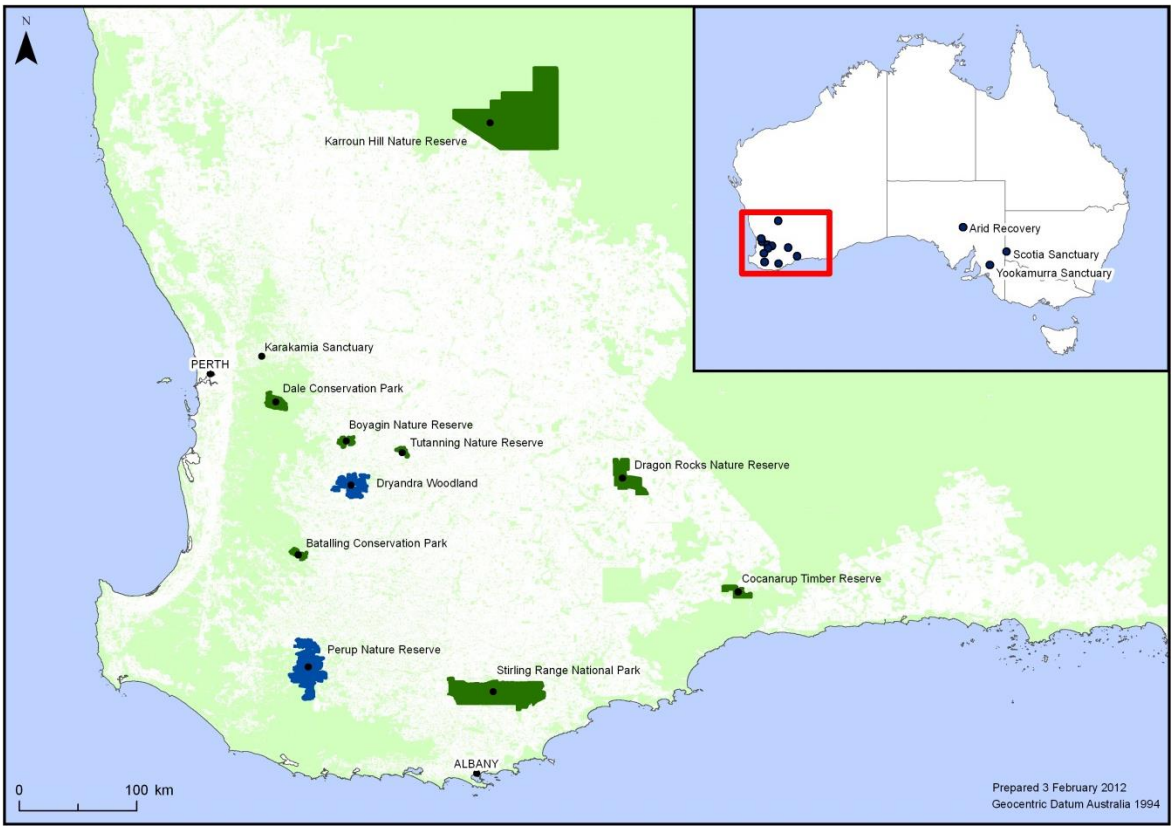
Fig. 5. Body mass (mean ± 1 S.E.) of numbats at Scotia Sanctuary. The 'at release' category only relates to animals supplemented from Perth Zoo and refers to their mass upon release at Scotia after collaring one or two weeks earlier at Perth Zoo. Male numbats captured in Stage 1 were translocated to Stage 2.

Fig. 6. Recapture weights of female numbats in Stage 1 of Scotia Sanctuary.

Fig. 7. Mortality causes for radio collared numbats at Scotia Sanctuary separated based on their source.

Fig. 8. Habitat preferences of numbats at Scotia Sanctuary according to Jacobs' index.

Fig. 9. Termite abundance in each habitat at Scotia Sanctuary.



793

794 Fig. 1

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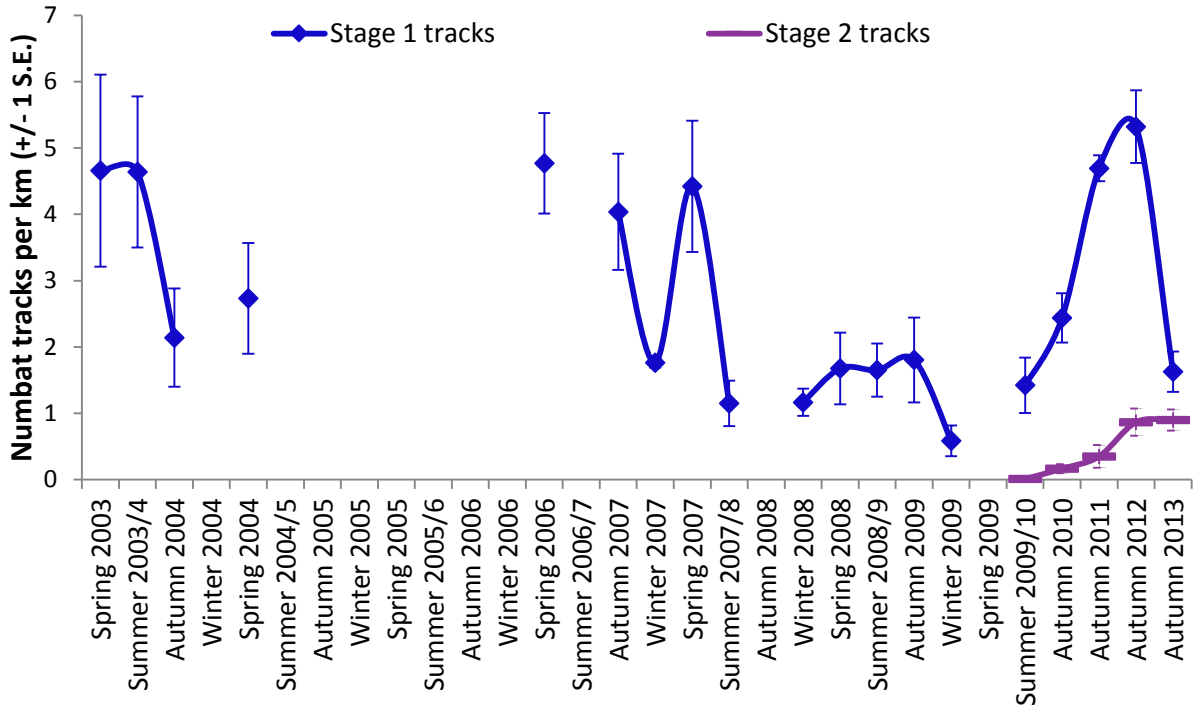

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797 Fig. 2

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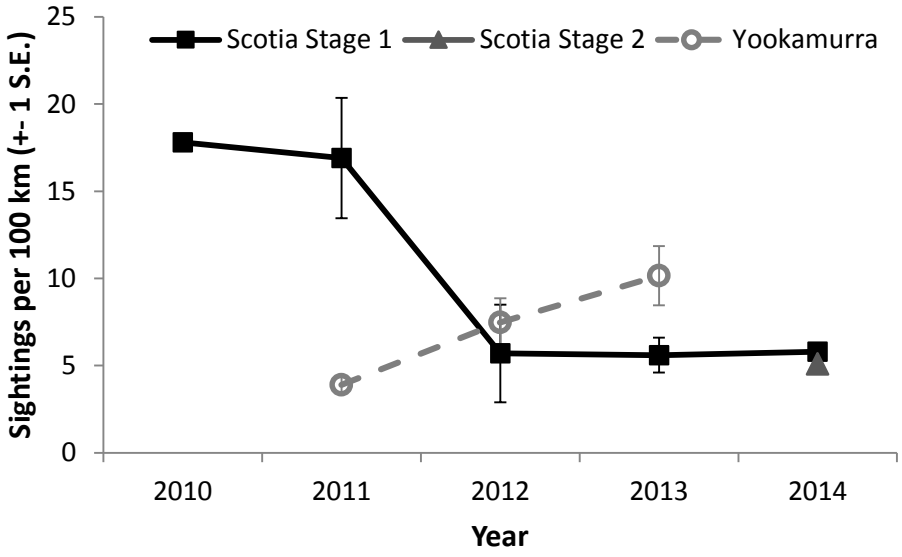

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800 Fig. 3

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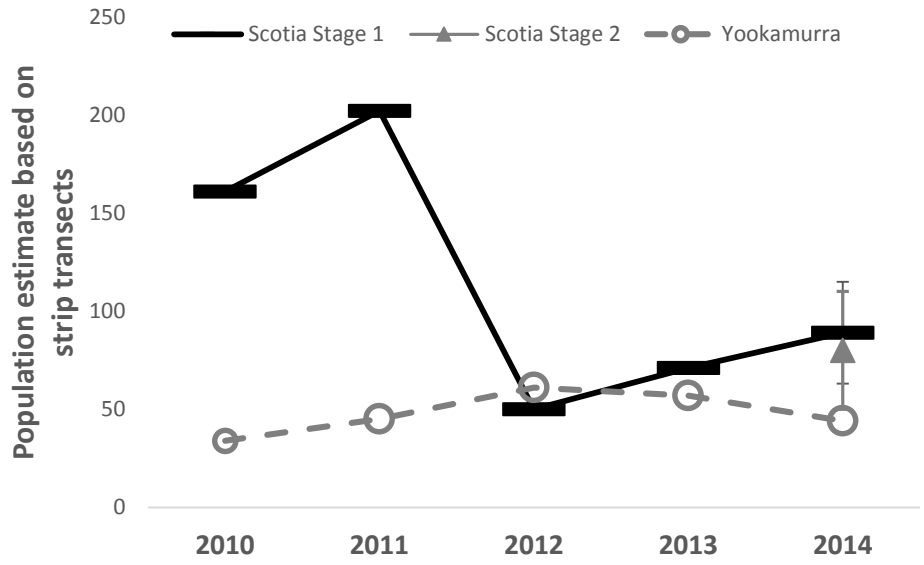
Scotia Stage 1
Scotia Stage 2
Yookamurra
Population estimate based on strip transects
250
200
150
100
50
0
2010
2011
2012
2013
2014

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803 Fig. 4

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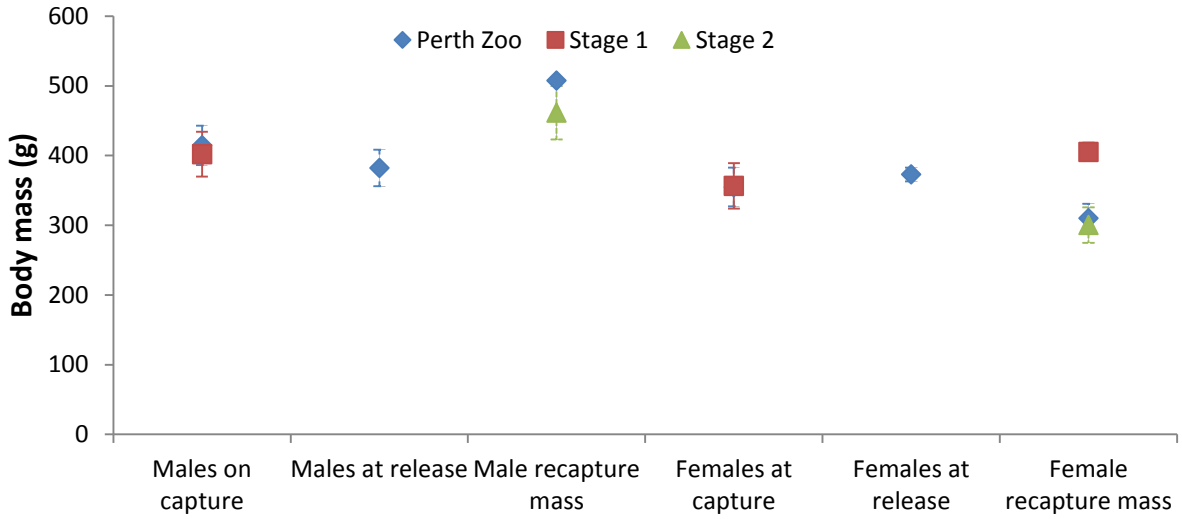

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806 Fig. 5
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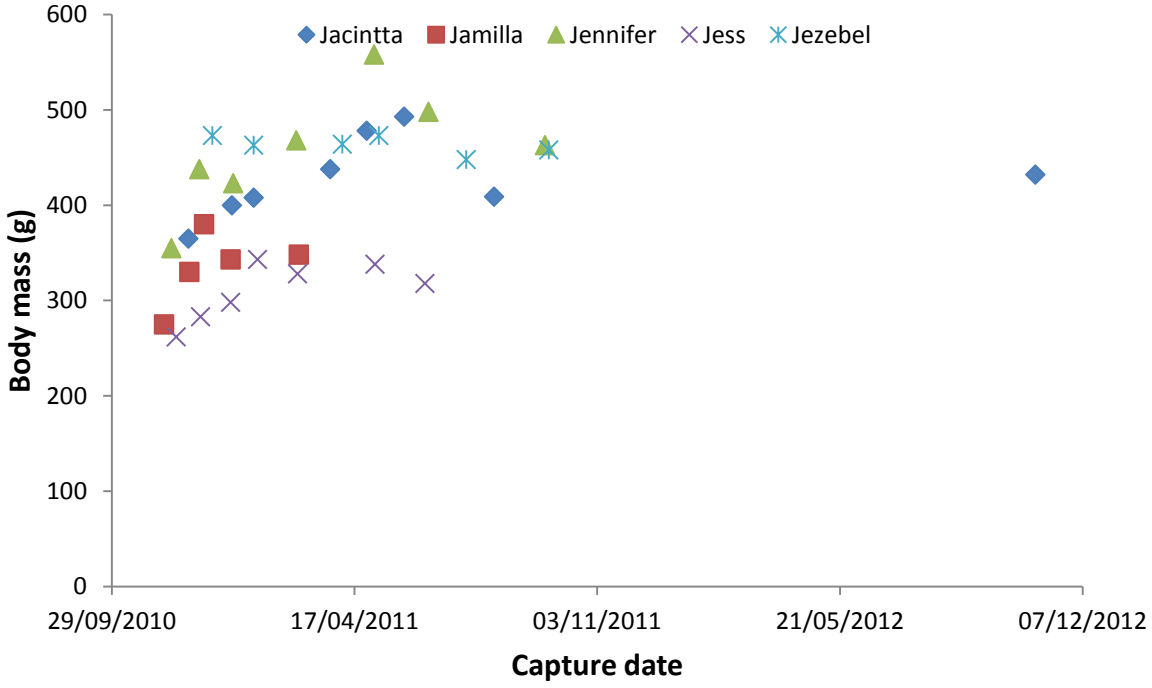

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817 Fig. 6
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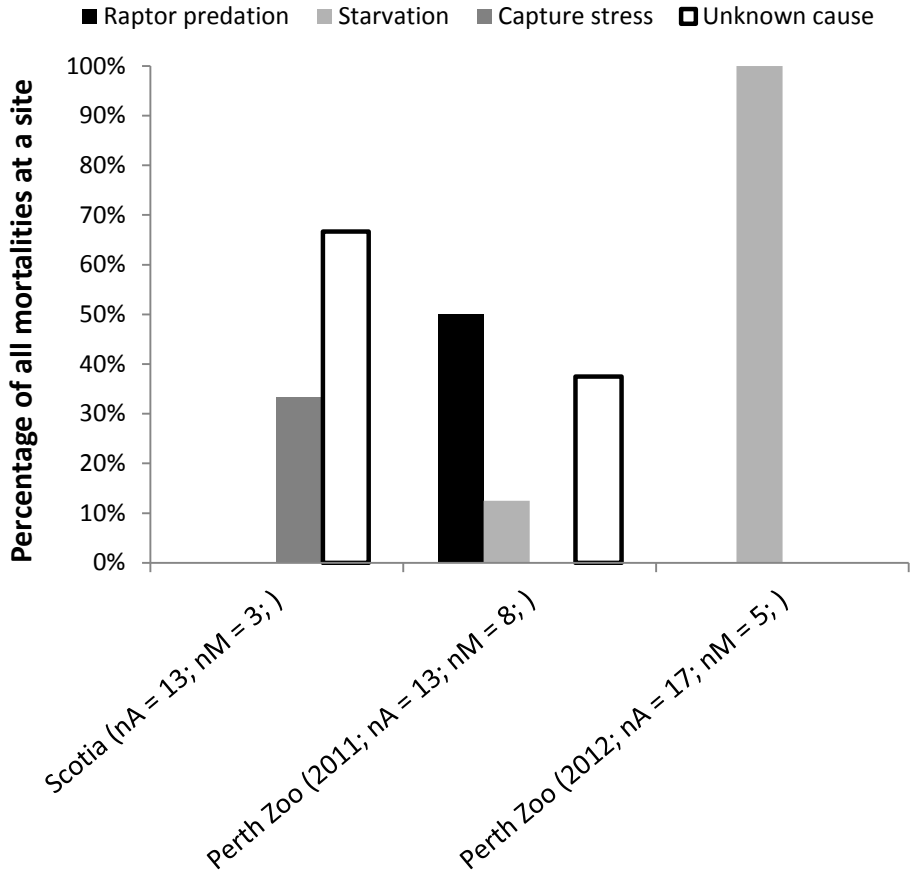

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821 Fig. 7
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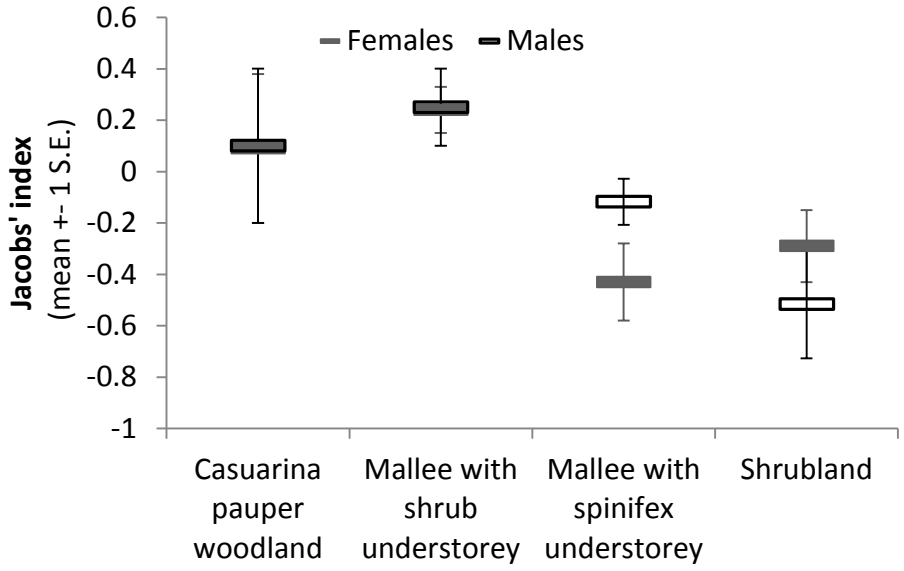

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825 Fig. 8

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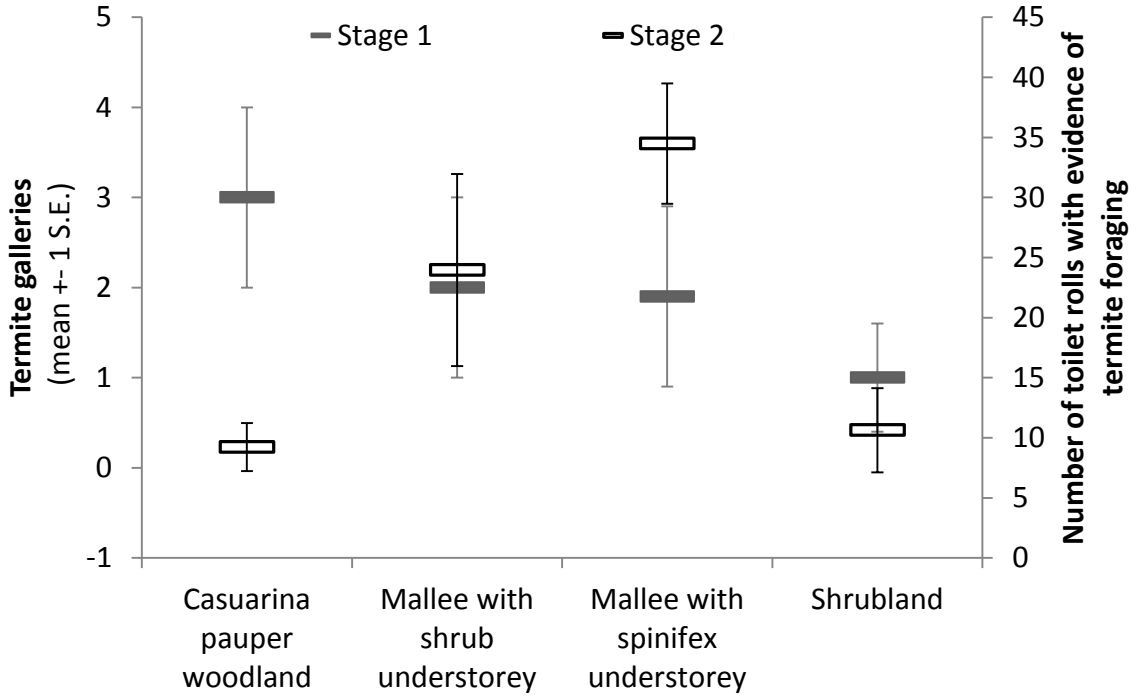

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828 Fig. 9

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